

Mass hierarchy ^(and CP ν) with accelerator experiments

LBNE, NO ν A, NO ν A+, T2K, MINOS+(+), GLADE, CHIPS

Ryan Patterson
Caltech

Intensity Frontier Neutrino Subgroup Workshop
SLAC, March 6, 2013

Long-baseline approach to mass ordering

One-slide review of technique

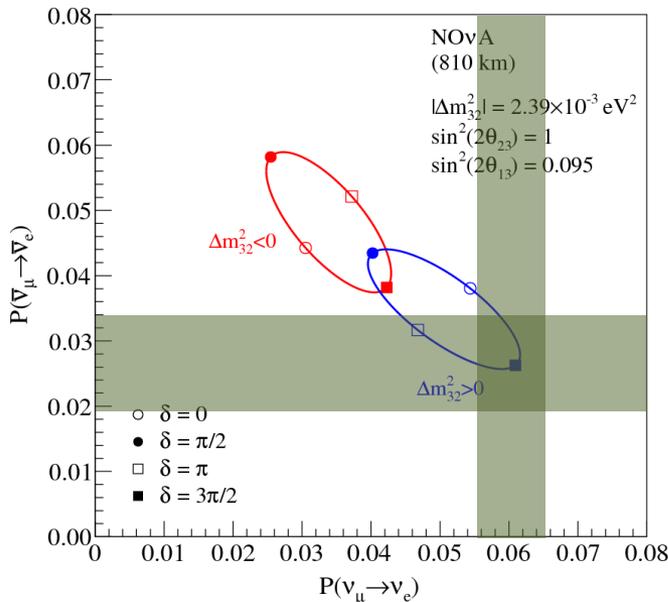
- All experiments in this talk are measuring:

$$P(\nu_\mu \rightarrow \nu_e, E) \quad \text{and} \quad P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e, E)$$

- Matter effects modify these probabilities by a calculable, baseline-dependent, hierarchy-dependent amount

- CP violation can also modify these probabilities

⇒ Both a “bug” (complicates hierarchy measurement) and a “feature” (allows CPv measurement)

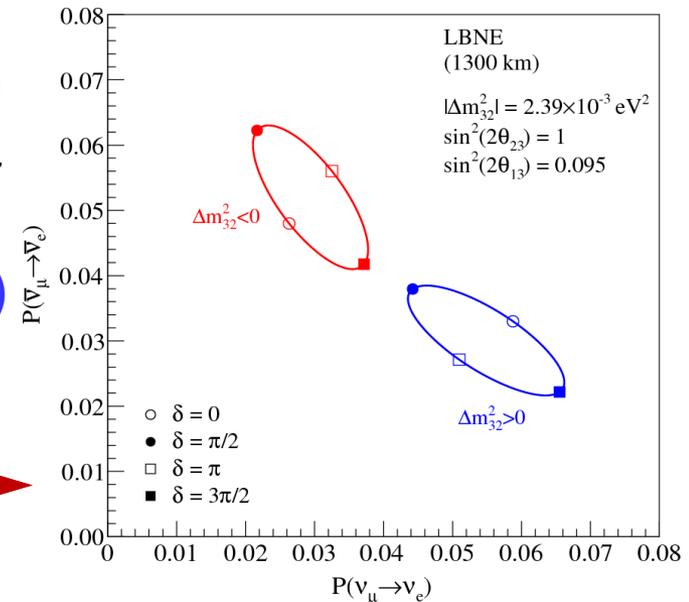


$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \quad \text{vs.} \quad P(\nu_\mu \rightarrow \nu_e)$$

shown at a particular L/E
for
both choices of $\text{sign}(\Delta m^2)$
and for full range of δ_{CP}

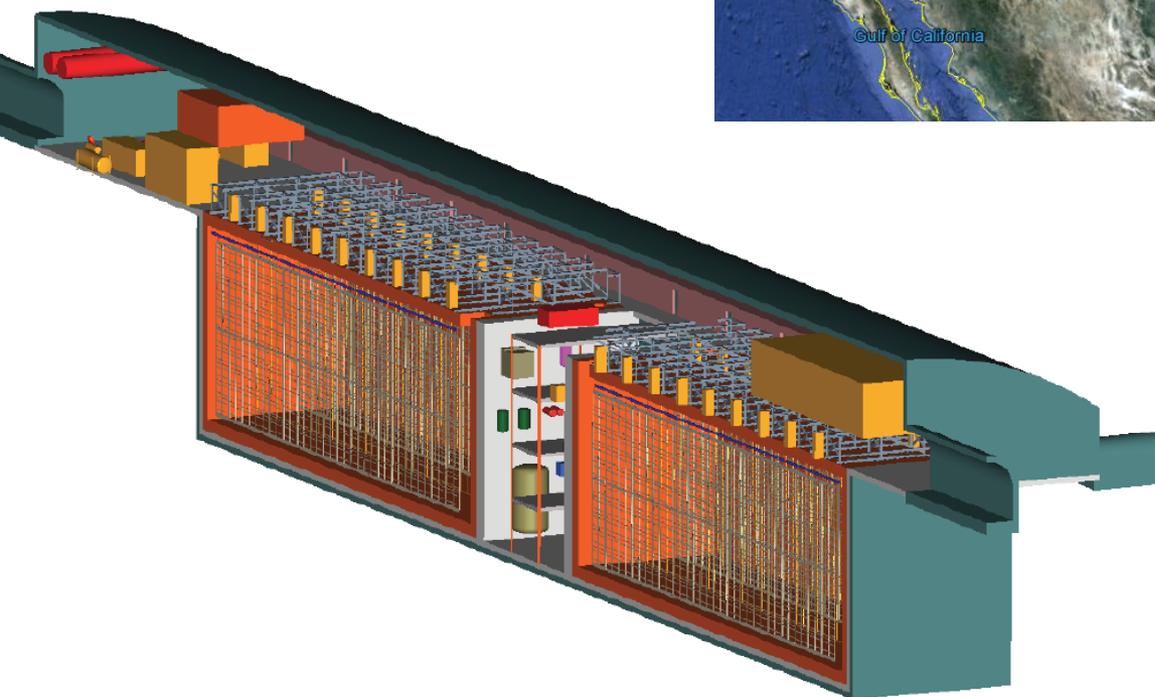
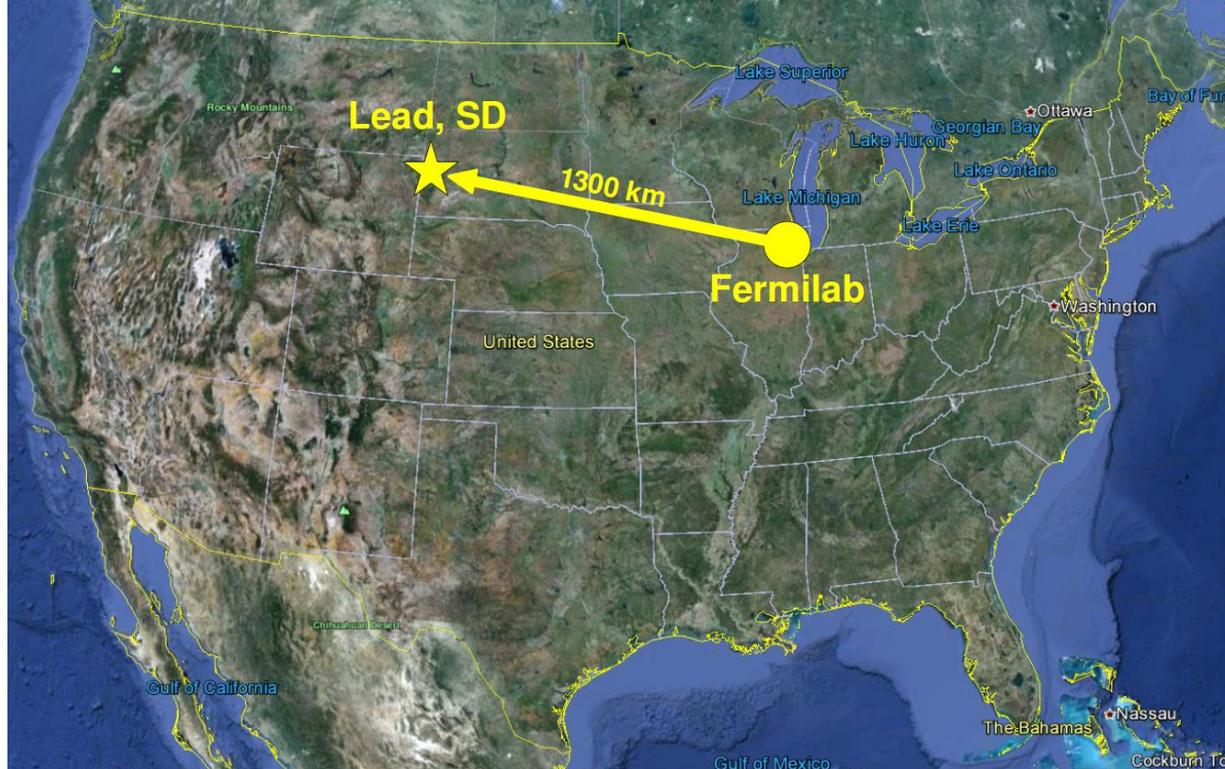
← 810 km

→ 1300 km



LBNE

- **1300 km baseline**
Matter effects too large to be confused by CPv, regardless of δ
- **New ν beam from FNAL**
- **LAr TPC detector**



- **Full program: 34 kton**
Price tag: ~\$1.5B
- **At odds with current budget scenarios**
- **Program reconfigured into “phases”**
- *Phase I: 10 kton @ Homestake*

LBNE 10 kton

- DOE guidance of **\$870M** does not cover underground FD or a Near Detector
- Cost with these (*i.e.*, including non-DOE funds) = **\$1.1B**

LBNE Phase I, 10 yr

Mass hierarchy:

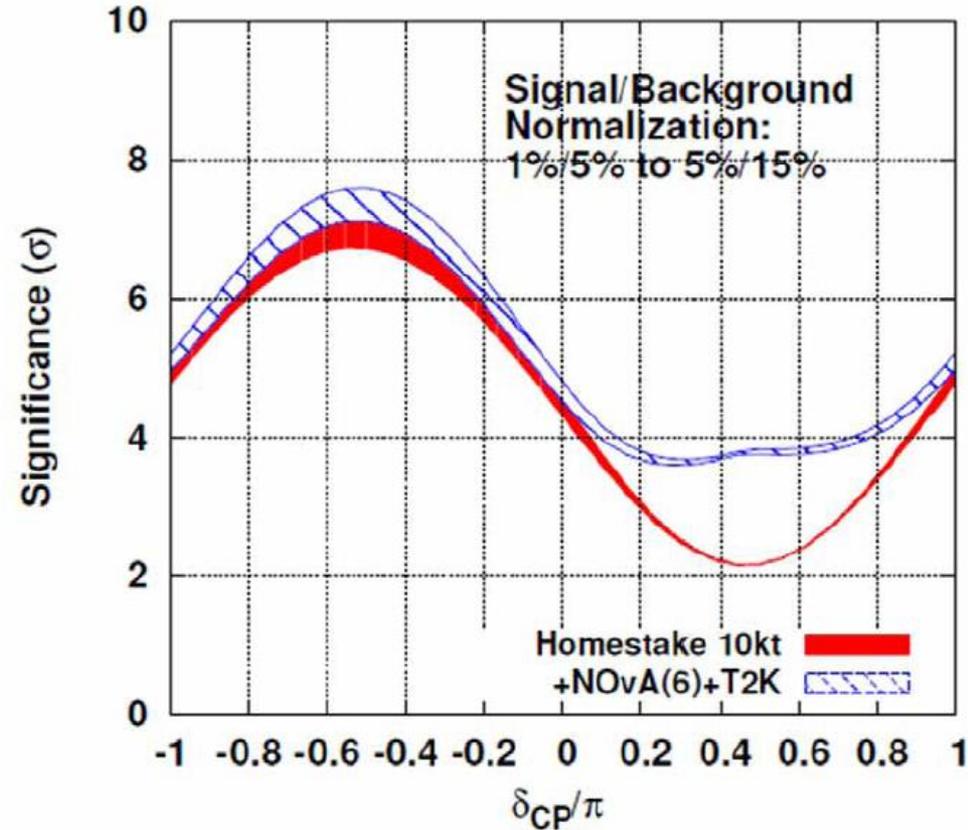
- > 2σ for **100%** of δ range
- > 3σ for **70%** of δ range
- > 5σ for **40%** of δ range

CPv coverage:

- > 2σ for **55%** of δ range
- > 3σ for **30%** of δ range

(N.B.: By definition, CPv coverage can never reach 100% of range)

Mass Hierarchy Significance vs δ_{CP}
Normal Hierarchy



Construction: **through 2023**

Operations: **c. 2023 – 2033**

LBNE 10 kton

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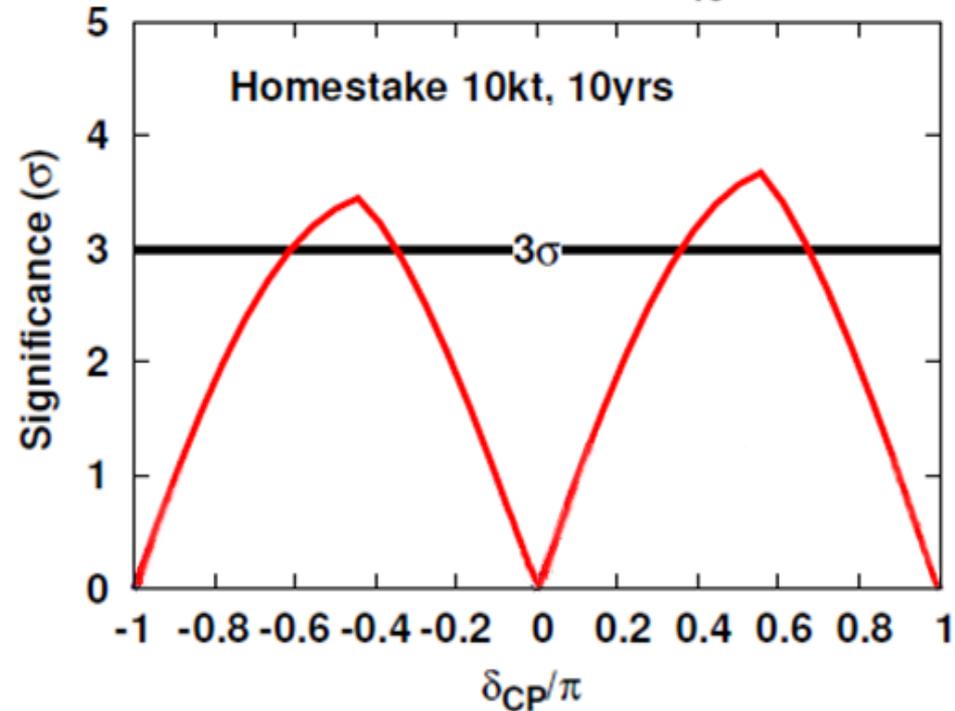
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CPV Significance vs δ_{CP}
10kt, NH(IH considered), $\theta_{13}=0.154(4)$

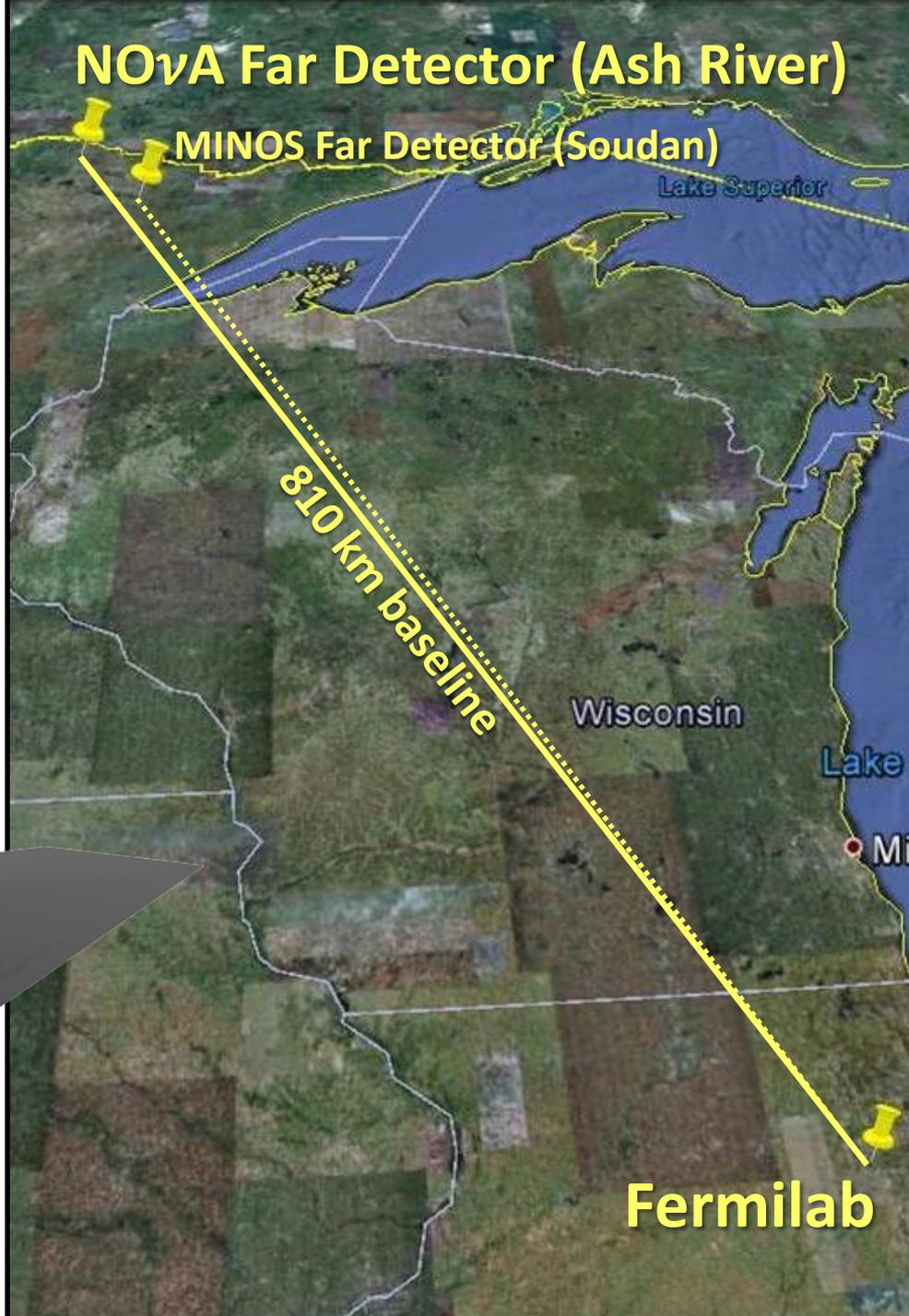
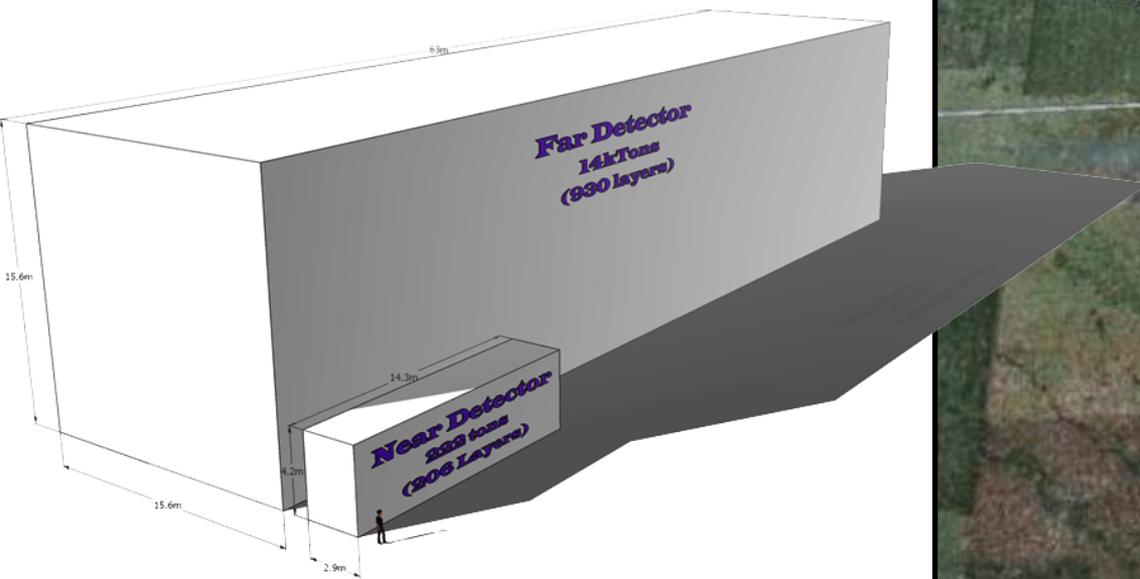


Construction: **through 2023**

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NOvA

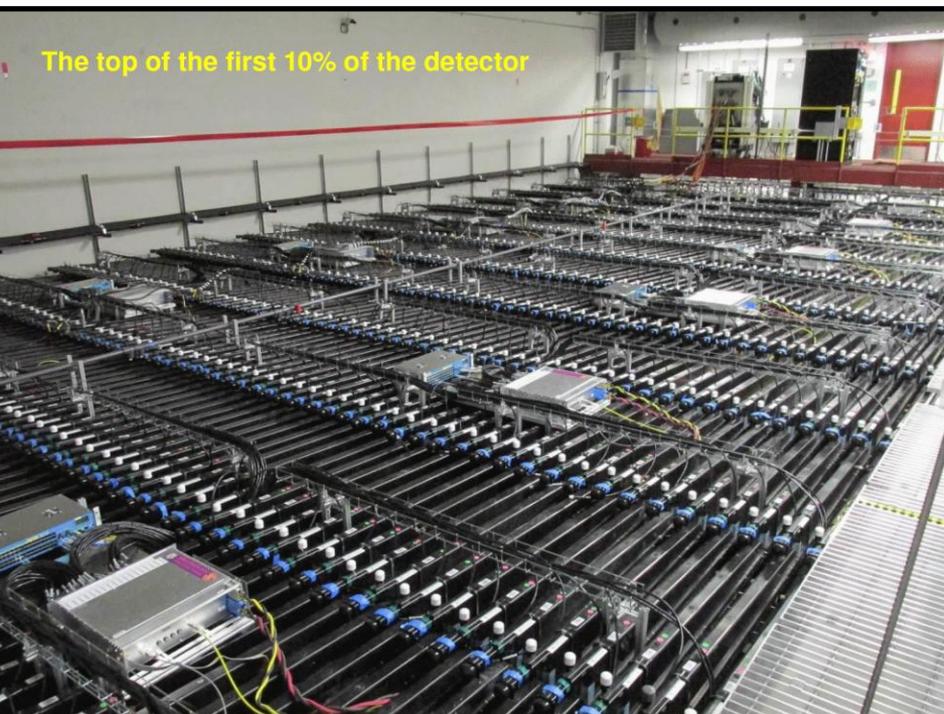
- Off-axis LBL experiment along the NuMI beam
- “Fully active” segmented LS detector, 14 kton
- *Construction well-underway, first light at FD last week (!)*



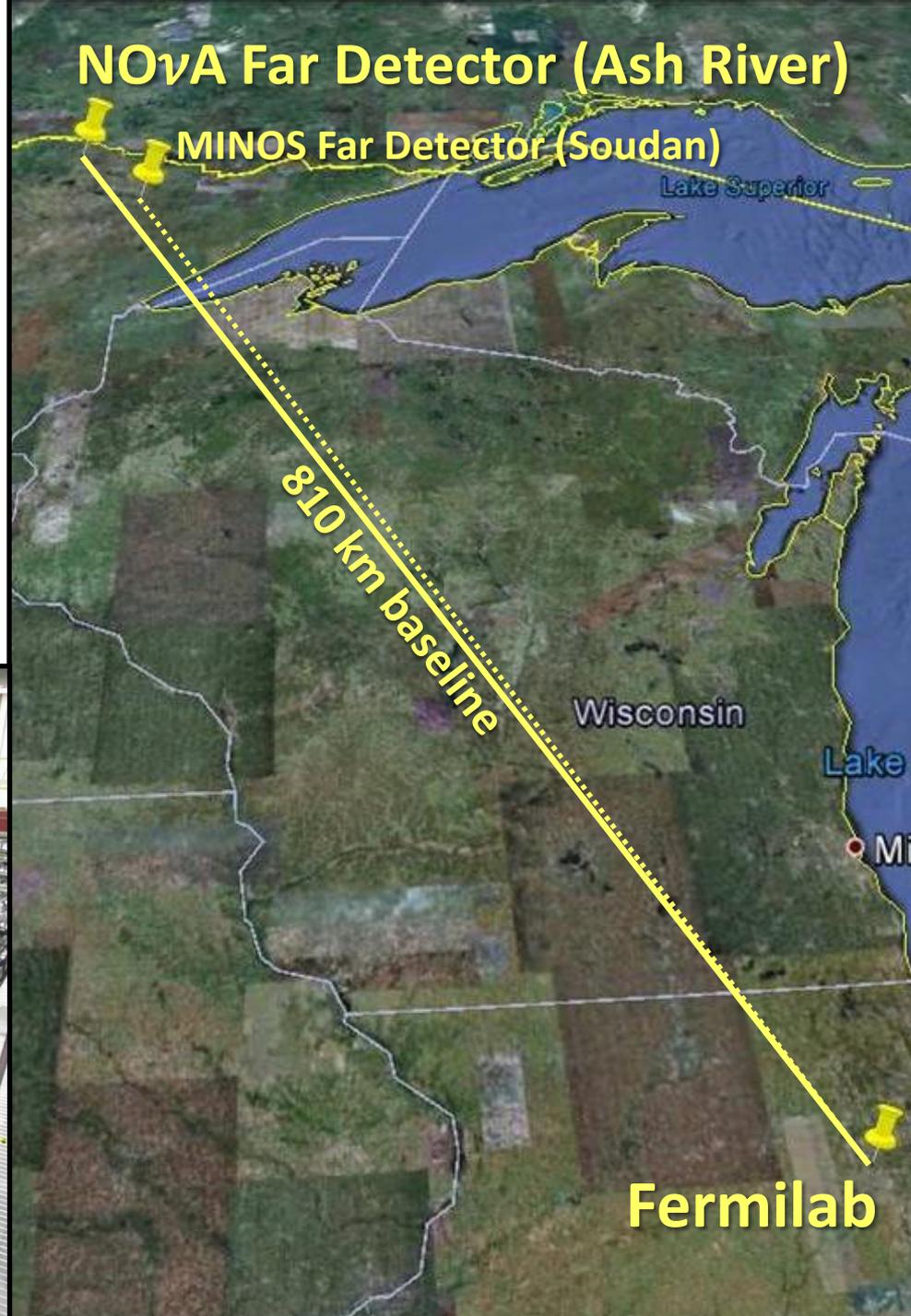
NOvA

- Off-axis LBL experiment along the NuMI beam
- “Fully active” segmented LS detector, 14 kton
- *Construction well-underway*, first light at FD last week (!)

The top of the first 10% of the detector



NOvA Far Detector (Ash River)



MINOS Far Detector (Soudan)

Lake Superior

810 km baseline

Wisconsin

Lake Michigan

Milwaukee

Fermilab

Life at 810 km: hierarchy

- *Away from the MH ambiguity*, MH reach is a matter of exposure
- *Near the MH ambiguity*, MH reach needs stats from other baselines

Generic NuMI experiment at ~ 800 km

Mass hierarchy:

$>??\sigma$ for 50% of δ range

**#-of- σ keeps
increasing with
more exposure**

**Accessing the rest
of δ range, though,
needs other baselines**

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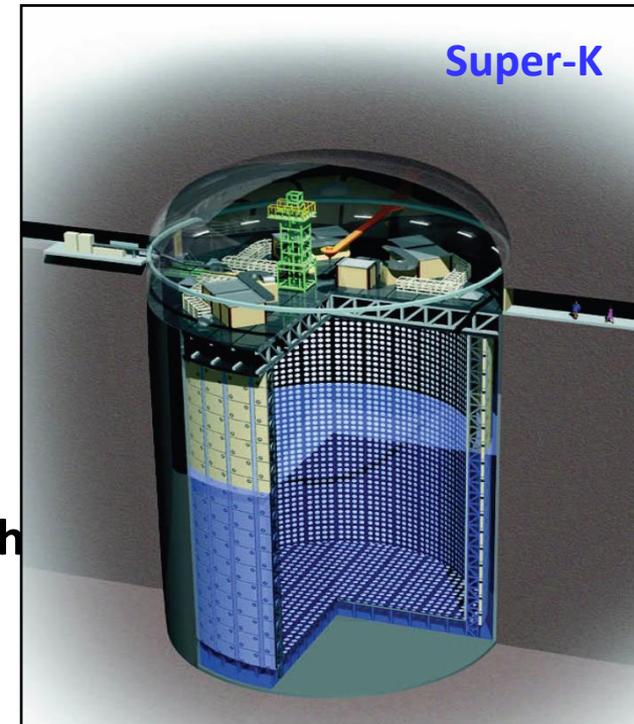
$>??\sigma$ for 50% of δ range

#-of- σ keeps increasing with more exposure

Accessing the rest of δ range, though, needs other baselines

T2K: 295 km baseline \Rightarrow minimal matter effect, so it helps disambiguate the “other” half of δ range. Not much impact on favorable half of δ range.

Can surpass 90% C.L. in degenerate region, but not much more without more T2K stats!



NOvA

- 700 kW beam from NuMI
- **Base program:**
 - Construction: underway**
 - Operations: 2013 – 2020**

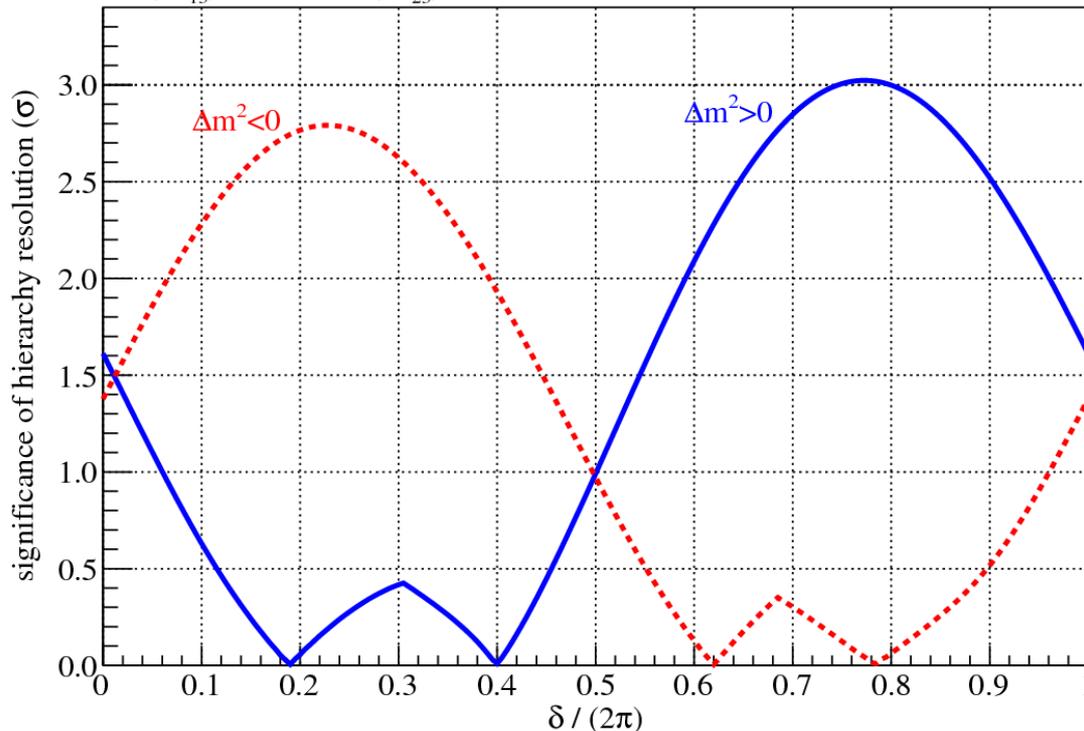
Not discussed: precision θ_{23} , maximality, octant, $|\Delta m^2|$, BSM physics, ...

NOvA, 6 yr

Mass hierarchy:

>2 σ for 35% of δ range

NOvA hierarchy resolution, 3+3 yr ($\nu + \bar{\nu}$)
 $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1.00$



4-kt additional construction, 10 yr run

NOvA+, 10 yr

Mass hierarchy:

>2 σ for 45% of δ range

>3 σ for 30% of δ range

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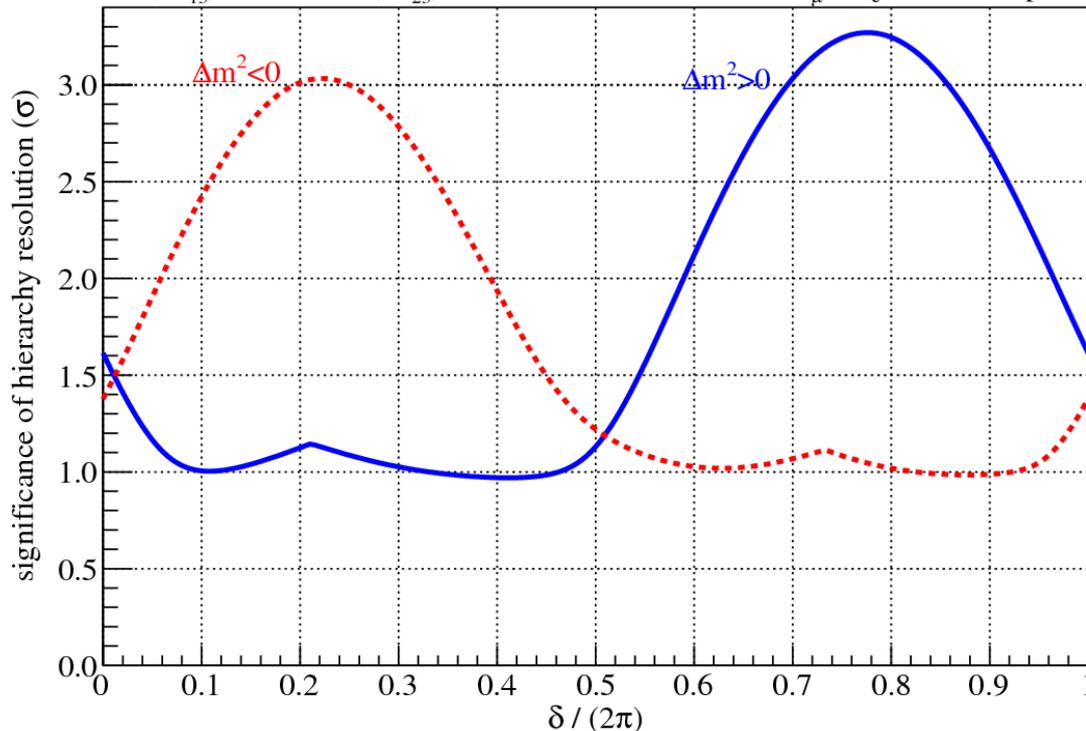
NOvA+, 10 yr

Mass hierarchy:

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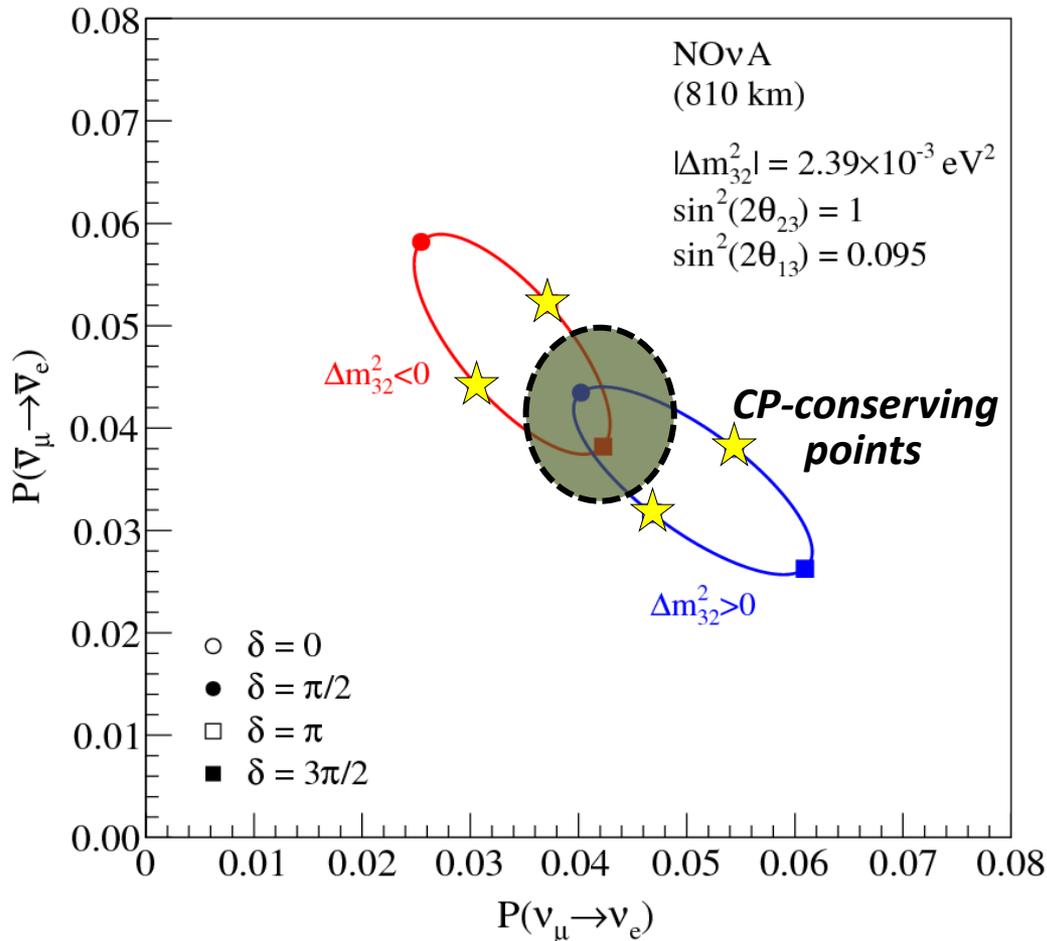
>3 σ for 30% of δ range

NOvA hierarchy resolution, 3+3 yr ($\nu+\bar{\nu}$)
 $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1.00$ Includes T2K $\nu_{\mu} \rightarrow \nu_e$ at 5.5×10^{21} p.o.t.



Life at 810 km: CP violation

- *CP violation search at 810 km – different story*
- *There is not a fundamental degeneracy for CPv discovery at 810 km*



For example at left...

*MH is ambiguous, but
 CPv discovery doesn't care*

*CPv is just a stats game at
 long or very long baselines*

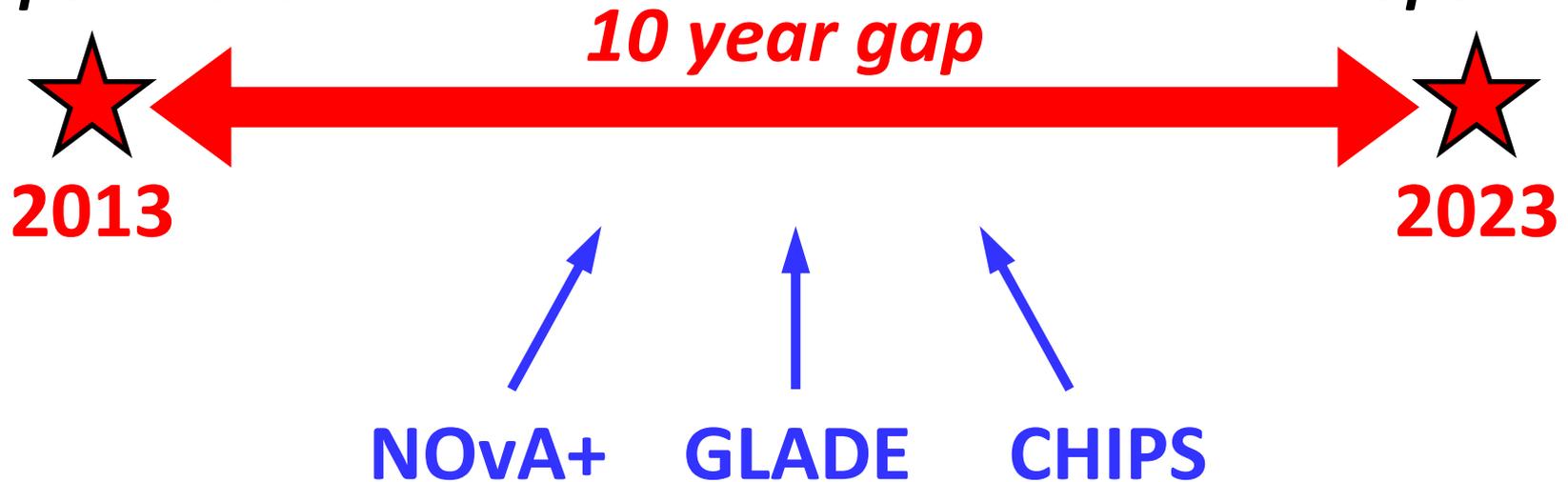
Side note: *observation of CPv
 could leave a bi-modal allowed
 region for the actual value of δ .*

*Deal with that later (LBNE). CPv
 observation is a goal on its own.*

Utilizing NuMI

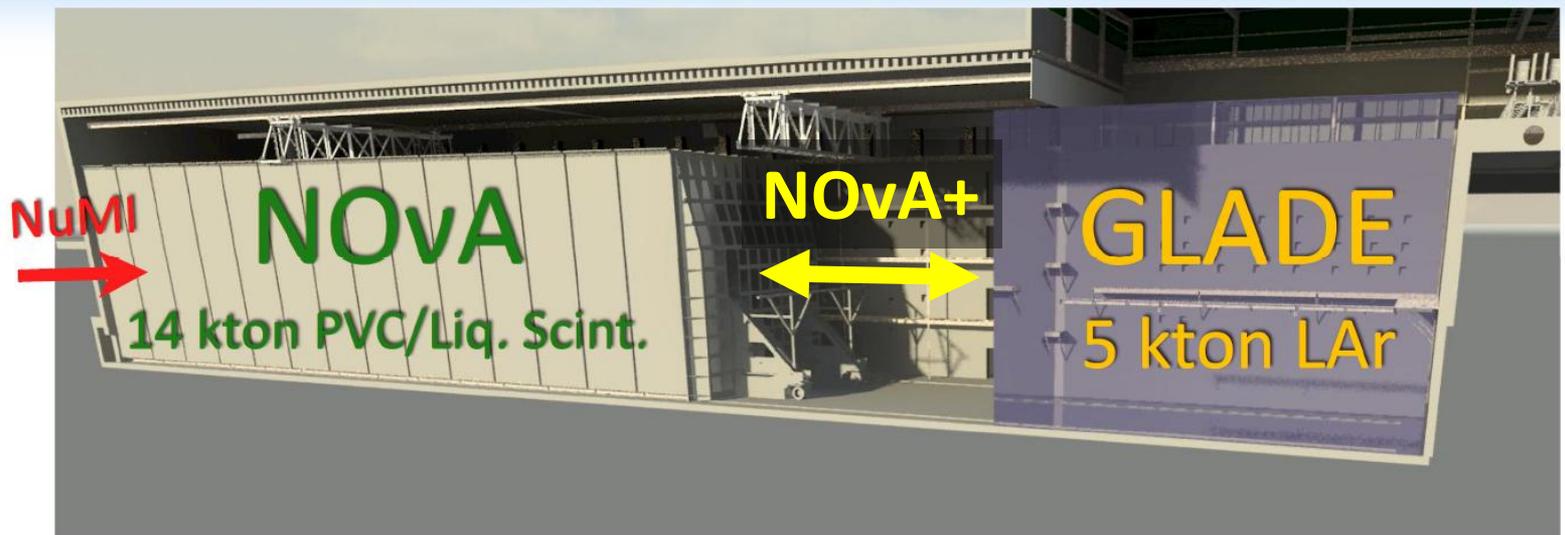
**Start of NOvA
FD operations**

**Start of LBNE
FD operations**



- **Aim for CPv** while increasing MH reach (*+ more stuff out of this talk's scope*)
- **Costs are low** (see next pages) relative to LBNE
⇒ ***Needn't burden existing LBL planning!***
- **$d(\text{physics})/d\$$ attractive**

NOvA+ and GLADE



NOvA+:

+4 kton mass and 10 yr run (instead of 6 yr)
Cheap! \$6M/kton if production lines are not stopped
(else, upper bound of \$9M/kton)
⇒ **Cost: \$30M** (+ operations)

GLADE:

Use free **NOvA assembly space**
18m x 18m x 24m maximum volume
Can house detector prototypes for LBNE and LBNO
(the "G" stands for "Global")
⇒ **Cost: \$150M** (+ operations)

NOvA+ and GLADE

NOvA, 6 yr

Mass hierarchy:

>2 σ for 35% of δ range

CPv coverage:

stats limited

+\$30M



NOvA+, 10 yr

Mass hierarchy:

>2 σ for 45% of δ range

>3 σ for 30% of δ range

CPv coverage:

>2 σ for 20% of δ range



+\$150M



GLADE, 6 yr

Mass hierarchy:

>2 σ for 55% of δ range

>3 σ for 40% of δ range

CPv coverage:

>2 σ for 45% of δ range



*here, includes NOvA+,
but doesn't have to*

*(Sensitivity calc. rule-of-thumb:
5 kton GLADE is about equal
in statistical power to 14 kton NOvA)*

CHIPS

- 100-kton water Cherenkov
⇒ *with prospects for staging*
- NuMI off-axis
- Use defunct mining pit →
(*would need filtration*)
- Benefiting from prior WC tech.
and deployment R&D
- Could be operational in <4 yr



Floating platform used for aquaculture
(*Shown here in open water, not in calm mining pit*)



**“Cherenkov
detectors
In mine
PitS”**

CHIPS

- 100-kton water Cherenkov
⇒ *with prospects for staging*
- NuMI off-axis
- Use defunct mining pit →
(*would need filtration*)
- Benefiting from prior WC tech. and deployment R&D
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- Closer to beam axis, broader spectrum
⇒ δ_{CP} info from shape
- Cost / event ID optimization underway re: PMT layout
(*e.g., reduced coverage on upstream side*)

+\$120M
→

CHIPS, 6 yr

Mass hierarchy:

>2 σ for 55% of δ range

>3 σ for 35% of δ range

CPv coverage:

>2 σ for 65% of δ range

includes 10 yr NOvA

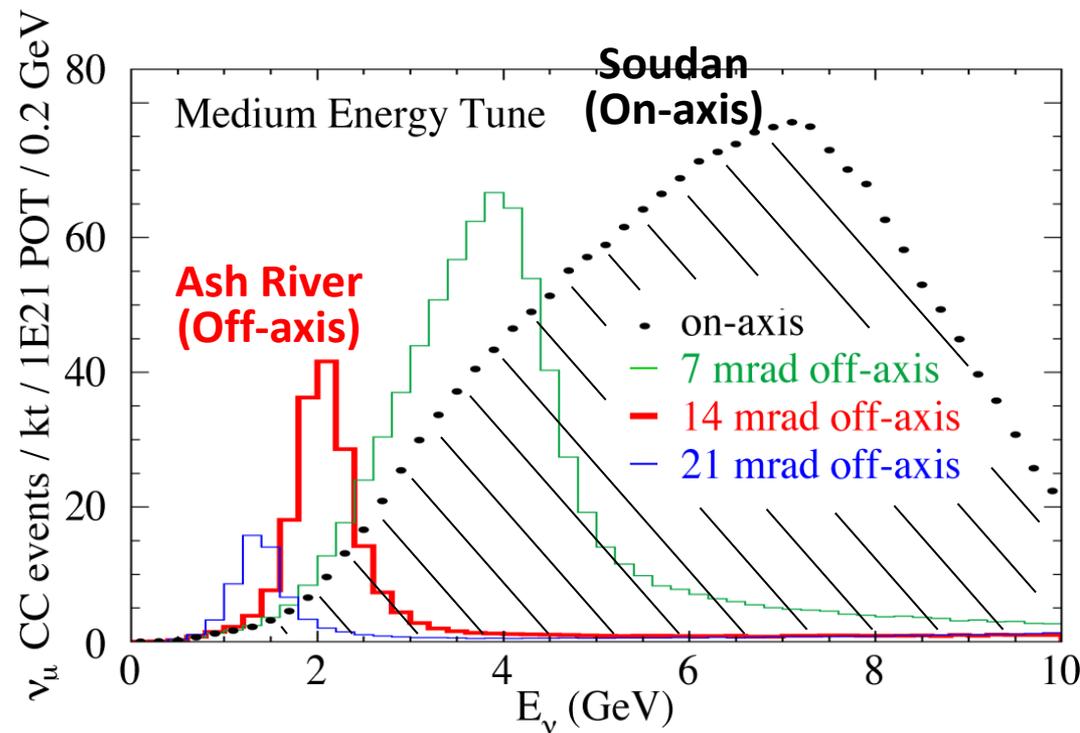


MINOS+(+)

- 3000 CC events/yr at MINOS+
- High-stats probe of 3-10 GeV region at 735 km
 - ⇒ Precision disappearance, NSI searches, sterile ν , ...

“MINOS++”

- ⇒ Idea to add new layers of scintillator strips
- Advocates are working on **cost, sensitivity estimates**
- Of note for this MH session:
Impact on MH reach likely to be minimal
 - ⇒ “small” FD mass, NC backgrounds, L/E not ideal (if in medium-E tune)



Summary

(Note: these costs buy you more than just this physics.
Full physics cases not described in this talk!)

<u>20-year time scale, 1300 km</u>		<u>Full scope in...</u>	<u>Hierarchy determination</u>	
LBNE	\$1100M (80% U.S.)	2033	2 σ @ 100%	3 σ @ 70%
<u>10-year time scale, 810 km</u>				
NOvA	funded	2020	2 σ @ 35%	
NOvA+	\$30M	2023	2 σ @ 45%	3 σ @ 30%
GLADE	\$150M	2023	2 σ @ 55%	3 σ @ 40%
CHIPS	\$120M	2023	2 σ @ 55%	3 σ @ 35%

Relevant: CP violation observation

LBNE	2 σ @ 55%	20 years out
Utilizing NuMI	2 σ @ 45-65%	10 years out

Note: Two different experimental niches here

\Rightarrow 2x in time scale, 10x in cost (programmatically compatible!)



- Get new physics cheaply and quickly (MH, CPv)
- 10 years later, LBNE handles open questions (MH if degen., δ value, ...) and provides tremendous precision toward model-building/testing era of neutrino physics

Summary

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**See Kathy Turner's talk:
An emphasis that continual physics output
is essential to competing with other fields.**

Utilizing neutrino 20 @ 45 55% 10 years out

Note: Two different experimental niches here

⇒ 2x in time scale, 10x in cost (programmatically compatible!)



- Get new physics cheaply and quickly (MH, CPv)
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Extras

LBNE

What 34 kton gets you

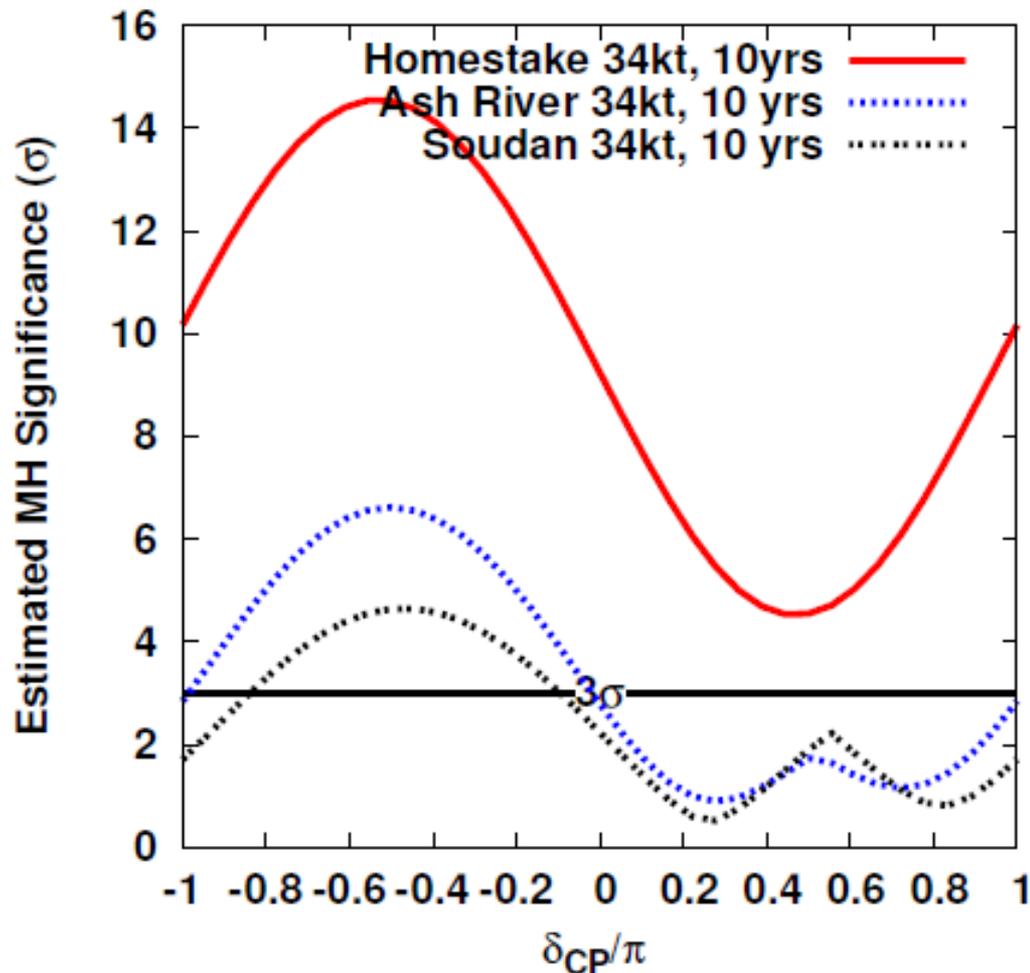
- 10 yrs of 700 kW operation with a 34 kton FD at Homestake

LBNE 34 kton, 10 yr

Mass hierarchy:

- >3 σ for 100% of δ range
- >5 σ for 85% of δ range

Mass Hierarchy Significance vs δ_{CP}
34kt, NH, $\theta_{13}=0.154(4)$



LBNE

What 34 kton gets you

- 10 yrs of 700 kW operation with a 34 kton FD at Homestake

LBNE 34 kton, 10 yr

Mass hierarchy:

- >3 σ for 100% of δ range
- >5 σ for 85% of δ range

CPv coverage:

- >3 σ for 60% of δ range
- >5 σ for 30% of δ range

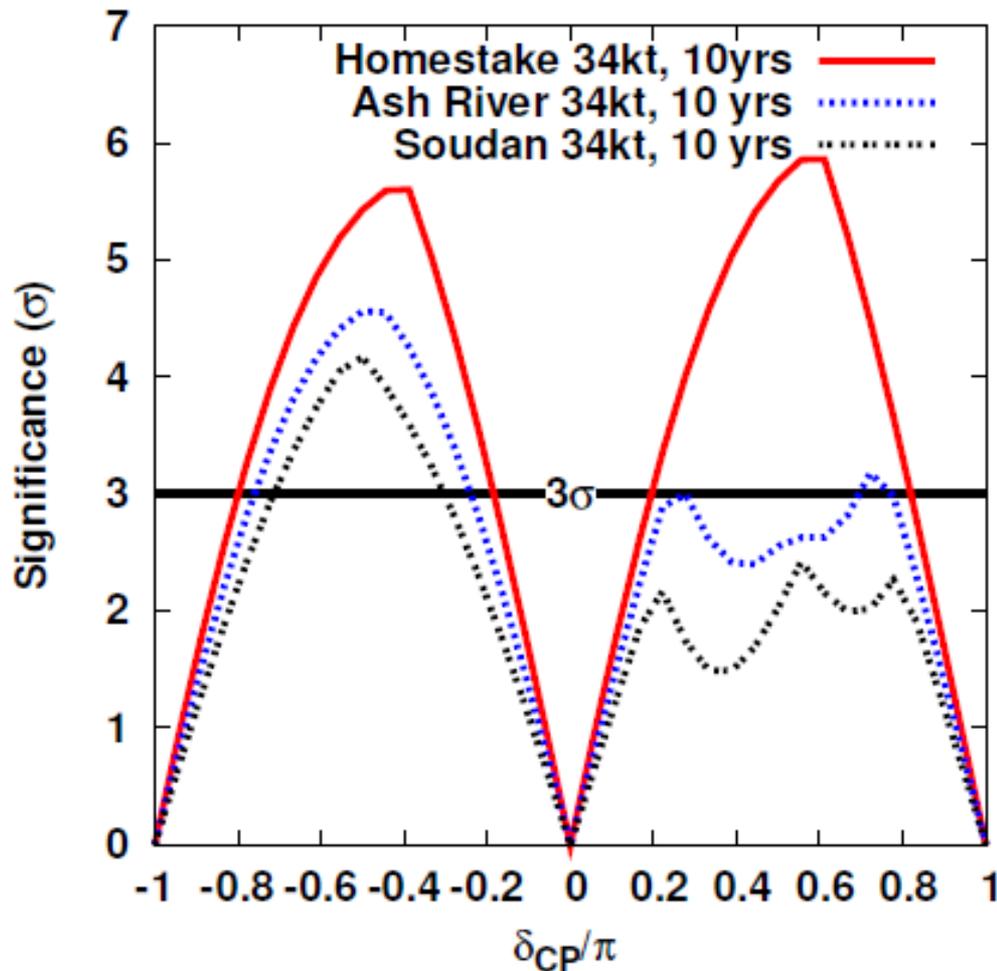
(N.B.: By definition, CPv coverage can never reach 100% of range)

A definitive experiment. Price tag: ~\$1.5B.

(also buys you other LBL ν measurements, atmospheric ν , proton decay, SN ν , ...)

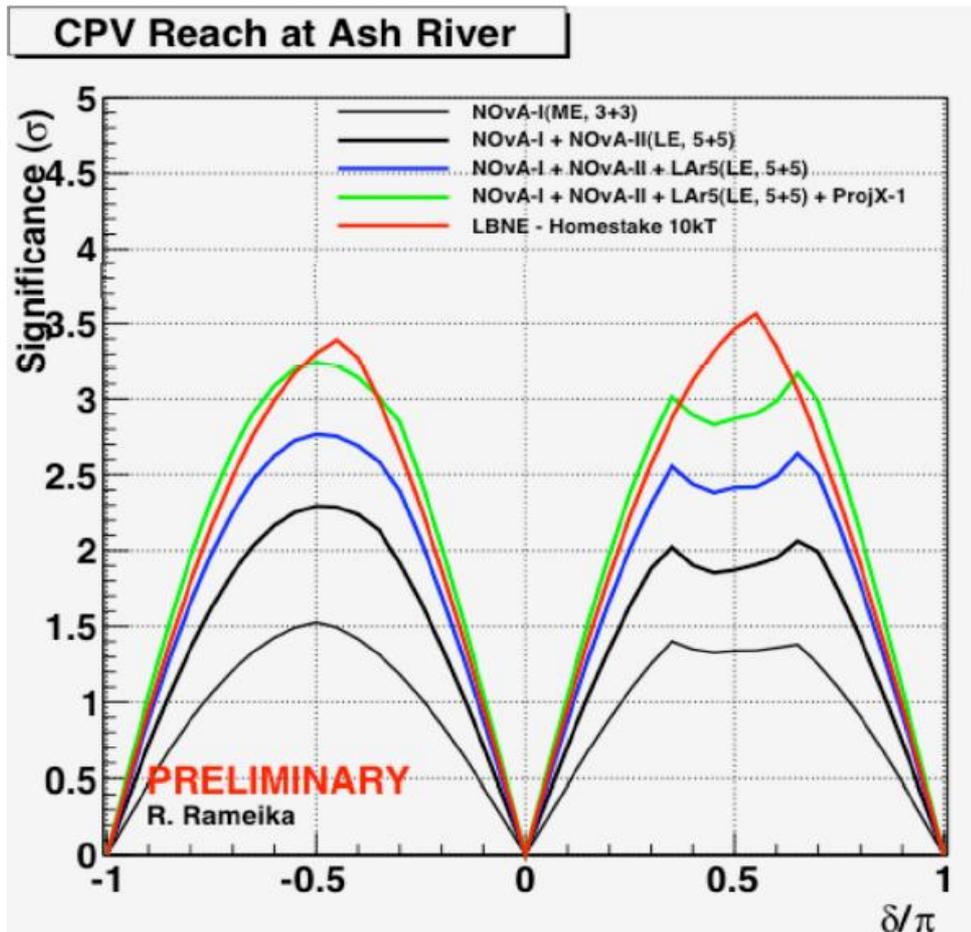
\Rightarrow At odds with current budget climate; reconfigured into “phases”

CPV Significance vs δ_{CP}
34kt, NH(IH considered), $\theta_{13}=0.154(4)$



Life at 810 km: CP violation

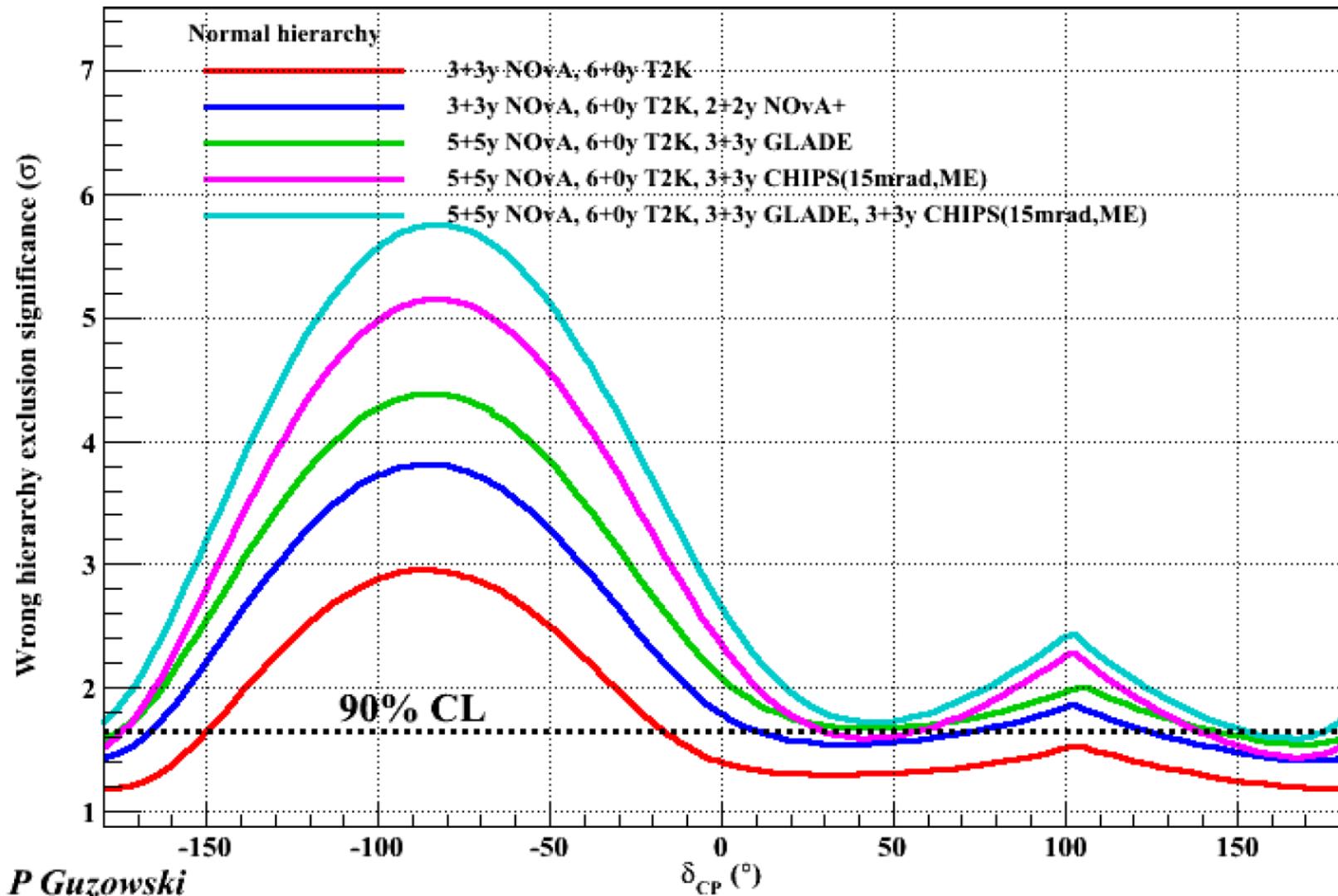
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Colors of note here:
10 kton LBNE
Ash River w/ similar stats

A GLoBES combination of NuMI prospects

(*P. Guzowski*)



Numbers for NOvA (1 on horiz axis), NOvA+ (2), [NOvA+]+GLADE (4)
(R. Patterson; see NOvA+ whitepaper for more detail)

